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YIELD RESPONSE OF DRYLAND CEREALS IN MALI TO FERTILIZER: INSIGHTS FROM HOUSEHOLD SURVEY DATA

By

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Abstract

In Mali, over 60% of the population lives in rural areas and about half of them live under the poverty line (World Bank 2017). Since most rural people depend on agriculture as their main source of livelihood, increasing agricultural productivity is crucial for decreasing poverty. This article explores the effectiveness of nitrogen fertilizer for increasing dry-land cereal crop yields.

Using the LSMS-ISA and a Sudan-Savanna dataset, simple econometric analysis suggests there is little effect of nitrogen fertilizer use on crop yields. However, when we account for the endogeneity of fertilizer use, we find yield response rates that are within the range reported in the literature. As expected, sorghum yields have a lower response to fertilizer than maize yields. Dryland cereal yield responses to fertilizer are stronger in the Sudan Savanna region (sample) than nationwide (nationally-representative dataset), highlighting the importance of agroecological factors and farming system. Soil texture and practices (anti-erosion structures) affect both yields and estimated effects of fertilizer. We also find phosphorus to be a binding constraint in increasing agricultural productivity. While most emphasis in the literature is placed on understanding nitrogen fertilizer use, it is crucial to promote balanced use of fertilizers so that other complementary nutrients are available in the soil.

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Tables and Figures

1. Introduction

In Mali, over 60% of the population is rural and half that segment lives below the national poverty line (World Bank, 2017). Most rural people depend on agriculture as their main source of livelihood. Dryland cereal crops, such as maize, millet and sorghum account for between two-thirds and three-quarters of all cultivated land depending on the years. Over recent decades, production of dryland cereals has grown primarily through expansion of cultivated area rather than intensification, which is unsustainable. Despite continued release of improved varieties, millet and sorghum yields have stagnated, with national averages hovering below 1 t/ha. Meanwhile, national average maize yields have risen from 1.4 t/ha from 2001/05 to 2.3 t/ha in 2010/15 (CountryStat 2017). Mali is West Africa's third largest producer of maize even though it stands fifth in the area harvested, with the highest average yields among all 15 maize-producing countries in the region (Abate et al. 2015). Nonetheless, as is common throughout Sub-Saharan Africa, maximum yields for improved maize varieties in farmers' fields remain substantially below yield potential based on experimental conditions (4-6 t/ha according to Coulibaly 2008; Macauley and Ramadjita 2015) given the challenges of growing conditions and incomplete input markets.

Inadequate use of mineral fertilizer has often been pinpointed as a cause of stagnating productivity in dryland cereals in Sub-Saharan Africa (NEPAD 2003: 47). In 2008, the Malian government decided to reinstate an input subsidy program with the aim of boosting cereal productivity through improved access to fertilizer while contributing to food and nutrition security via higher income and lower consumer prices (Kone 2016; Smale, Diakité and Keita 2012). Fertilizer subsidies now constitute the largest expense item, accounting for about 25% of all government spending on rural development (Theriault, Smale, and Assima Forthcoming). Given that extremely small amounts of fertilizer are currently used on either sorghum or millet, we do not expect the fertilizer subsidy program to have a generalized effect on production decisions nationwide. However, Theriault, Smale and Assima (forthcoming) found a significant impact on fertilizer use and yields for sorghum and maize in the Sudan Savanna, which is a region suitable for agriculture. A more resounding critique of policy regarding mineral fertilizer is that the soils of Mali are generally deficient in specific nutrients and that soil organic matter is necessary for effective integration of nutrients (Dicko et al. 2016; Mason et al. 2014). Long-term losses due to soil erosion have been documented (Bishop and Allen 1989), although these have been offset in some areas by successful resource management programs (e.g, Tappan and McGahuey 2007).

Despite the policy emphasis on mineral fertilizer, few studies have systematically examined the cereal yield response to fertilizer in Mali—which is fundamental for evaluating program impacts. An important exception is the analysis of farm experimental data by Dicko et al. (2016), who estimated response functions for nitrogen (N), phosphorus (P) and potassium (K) on maize, rice and millet across the four bioclimate-based agro-ecological zones of Mali. In general, the authors found that economic optima of nutrient application rates diverged from recommended application rates, which remain uniform throughout the country and vary only by crop.

We know of only two other studies that address productivity of dryland cereals in Mali, both of which using data collected in farm household surveys rather than under experimental conditions. Using a 12-year farm household panel dataset (1994-2006) from Mali's Sikasso region, Foltz et al. (2015) found a strongly significantly response of maize yields to fertilizer, concluding that increasing fertilizer use has driven most of the maize productivity growth. Sikasso is a region of high productivity potential for maize, where it is grown in rotation with cotton. Applying a stochastic production frontier to nationally-representative data from the Living Standards Measurement Survey-Integrated Survey of Agriculture (LSMS-ISA), Ahmed, Gaskell and Gautam (2017) found no significant response of yields to fertilizer across crops and regions. We know of no published analyses of yield response to fertilizer in sorghum or millet that employ farm household data.

We thus contribute to a sparse literature by estimating dryland cereals response functions (maize, millet and sorghum) using two farm household survey datasets. The first dataset, the Living Standards Measurement Survey-Integrated Survey of Agriculture (LSMS-ISA), is nationally-representative and includes information on all three crops (sorghum, millet, maize). The second dataset, collected by a research team from the Institut d'Economie Rurale, was collected only in the Sudan Savanna, and focused on sorghum and maize. Both datasets were collected during the 2014/2015 growing season. In estimating our yield response functions, we employ a combination of econometric approaches to compare and check the robustness of our findings.

We find significant but small effects of nitrogen on dryland cereal yields when analyzing the nationally-representative LSMS-ISA data. In the sample collected within a smaller geographical area of the Sudan Savanna, nitrogen response rates in sorghum and maize are larger in magnitude. This highlights the heterogeneity in maize yield responses to fertilizer across agro-ecological zones/farming systems. Estimated marginal products are within the range cited in the existing literature for West Africa (Theriault, Smale, and Haider 2017; Koussombe and Nauges 2017), but lower than those cited for Eastern and Southern Africa (Sheahan et al. 2013; Marenya and Barrett 2009; Xu et al. 2009). In the analysis of the Sudan Savanna data, phosphorus proves to be a binding constraint.

2. Methods

2.1 Data sources

First, we utilize data from the Living Standards Measurement Survey-Integrated Survey of Agriculture (LSMS-ISA), which was conducted in Mali in two visits during the 2014-15 growing season. Summary information about the survey is provided in a document compiled by the Planification and Statistics Unit 2016). With probability of selection proportional to size of population as of the 2009 Census, the statistical sample is nationally representative of both rural and urban areas excluding the region of Kidal. The total sample size was limited by inability to collect data in some regions because of political insecurity, with the largest sample losses in the regions of Mopti, Tombouctou and Gao. The final sample includes about 3,804 households as compared to the planned sample of 4,218. The number of standard enumeration areas (SEs, or grappes) was 1070, with 80% in rural areas, including 2-3 households per grappe. Compared to LSMS surveys which focused on household consumption, expenditures and income, the LSMS-ISA survey also contains plot level data on input use and crop production. One-third of all plots inventoried by households in each SE were randomly sampled after grouping them by crop and crop association1. This procedure was necessary given that in Mali, large numbers of plots may be simultaneously cultivated by extended family farms, augmenting respondent burden and survey costs.

We conduct our analysis only on data from the main rural agricultural regions of Mali, excluding Tombouctou, Gao, and some observations around Bamako. Our analytical sample therefore covers the regions of Kayes, Koulikoro, Sikasso, Segou and Mopti. The dispersion of the sample across agroecologies and farming systems is illustrated in Figure 1a. Given the magnitude of this survey effort conducted under difficult logistical conditions, we encountered a number of limitations in the data. Data cleaning is described in the Appendix.

The second data source is a case study undertaken in the sorghum belt of Mali, which we use as a comparison since it is more focused on a specific farming system (Figure 1b). Survey details are provided in Smale et al. (2015) and Assima et al. (2017). The sample was drawn from a baseline census of all sorghum-growing households in 58 villages located in the Cercles of Kati, Dioila (both Koulikoro Region) and Koutiala (Sikasso Region) of Sudan Savanna, within the 800 mm isohyet. Villages surveyed included all those with fewer than 1000 persons that were listed as sites where the national research program and farmer associations had implemented activities since 2009. The multi-visit survey was conducted in four rounds from August 2014 through June 2015 by a team of experienced enumerators employed by the Institut d'Economie Rurale. The sample is representative of areas in the Sudan Savanna with some exposure to agricultural research outreach activities. For cereals, many sorghum growers also grow maize and millet in this region. Millet is also grown, but due to budget constraints, detailed plot information was collected only for sorghum and maize.

The sample of households was drawn with simple random sampling and augmented by five percent to account for possible non-responses, leading to a total of 623 households and an overall sampling fraction of 25%. Enumerators listed all plots operated by each sampled households. One plot was randomly sampled per crop and management type per household. The total analytical sample employed here after removing yield and fertilizer use outliers is 1,086 plots, including 421 sorghum plots and 665 maize plots.

In addition to the household survey data, this dataset includes soil nutrient indicators measured in laboratory tests conducted on soil samples by the Institut d'Economie Rurale, Sotuba, Mali. Soil samples could not be collected from all sorghum and maize plots due to budget constraints. Plots

[1] Pers. Comm. Assitan Traoré, Cellule de Planification Cellule de Planification et de Statistiques du Secteur Développement Rural (CPS/SDR), pers. Comm, June 15, 2017 and November 15, 2017.

were subsampled randomly within crop (sorghum, maize) and plot management (collective, individual) groups. Soil samples were obtained after the harvest by following a standard protocol with 8 sub-samples per plot collected in a zig-zag pattern, to assure overall plot representation (see Appendix 2). Laboratory analysis followed Sparks et al. (1996). The analytical sample for soil nutrients is 643 plots.

Rainfall data were downloaded and compiled from the Climatology Resource for Agroclimatology site of the National Air and Space Administration[2].

2.2 Econometric approach

Our objective is to quantify the effect of fertilizer use on the yields of dryland cereal crops using household survey data. To do so, we estimate the yield response model:

$$Y_i = \beta_1 F_i + \boldsymbol{\beta_2 I_i} + \boldsymbol{\gamma X_i} + \varepsilon_i \qquad (1)$$

The model is estimated by plot level regressions, where the dependent variable Y_i denotes the crop yield (kg/ha). The main explanatory variable is F_i, the quantity of fertilizer applied on plot i. Hence, the main coefficient of interest is β_1. Fertilizer quantity is measured in nitrogen kg/ha in order to standardize across different fertilizer types. The nitrogen fertilizer variable is created by summing up the nitrogen content from urea (46%), NPK (14%), DAP (18%) and other fertilizer (16.5%) applied on that plot.

Other than fertilizer, agricultural inputs I are also used on plots, and these are typically included in yield response functions estimated with either experimental or survey data. Accounting for other inputs is important because fertilizer is often used in conjunction to other inputs. For example, plots that apply more fertilizer may have more labor allocated to them. If we do not control for labor quantity, the coefficient on fertilizer will include the effect of labor and will overestimate the effect of fertilizer on crop yield. $\boldsymbol{X_i}$ is a vector of factors other than inputs that affect crop yield. Plot characteristics are important determinants of crop yield, and are included in $\boldsymbol{X_i}$.

The estimation strategies for equation (1) are tailored to the two data sets we use. Despite controlling for plot characteristics, $\boldsymbol{X_i}$, the estimate of β_1 may not be consistent. This is because there may be other omitted variables that explain crop yield and that are correlated with the quantity of fertilizer applied. For example, wealthier households may have higher crop yields because they can acquire more knowledge on efficient agricultural practices from radio, television or agricultural extension agents. They may also apply more fertilizer because they

[2] Accessed from http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov

have money or credit available to purchase fertilizer. Farmers may also choose to apply fertilizer on plots with soils that they observe to be more responsive.

However, there are many factors to consider – many of which are hard to quantify. Hence to eliminate household level confounding factors, in the LSMS model, we use household fixed effects to estimate model (1). Since the survey is cross-sectional and contains data from a single year, we compare yields on plots within the same household with varying levels of fertilizer applied. This allows us to control for any unobserved household level factors that explain crop yields and are correlated with the quantity of fertilizer applied.

While this estimation strategy can provide reliable estimates for β_1, there may still be additional concerns of omitted variables bias. Unobserved plot level characteristics are likely to affect crop yields. We can try to measure such variables, as in the case of soil samples collected in the Sudan Savanna, and include them as explanatory variables. For example, the soil organic matter partly determines the responsiveness of nitrogen fertilizer (Marenya and Barrett 2009). Such plot level omitted variables would lead to inconsistent estimates of β_1.

With the LSMS data, we use instrumental variables estimation, combined with household fixed effects, to overcome such issues and provide more robust estimates of the effect of fertilizer on crop yields. The instrument captures the general diffusion of fertilizer in the region where the household is located. In specific, we use the average fertilizer rate used across plots growing that crop in the grappe. The average excludes all plots cultivated by the household itself. The instrument is calculated by averaging the fertilizer application rate across 1 to 30 plots (on average the instrument is constructed using 3.5 plots). Hence, one instrument is created for nitrogen fertilizer.

The diffusion rate of fertilizer differs across crops, and hence the instrument varies within households that grow more than one crop. Since the identification strategy combines household fixed effects with instrumental variables estimation, it is necessary that the instrument varies within households. If we estimate a yield-response function for each crop separately, the instrument will not vary within households so we will be unable to use household fixed effects with instrumental variables estimation[3]. Thus, we present separate regressions for millet, sorghum and maize that have been estimated with household fixed effects only.

We expect the instrument to be correlated with the potentially endogenous variable because it captures the general availability of fertilizer in the locality. We do not expect the fertilizer allocation of households to directly influence the crop yields of other households – except through the increased use of fertilizer. Under these assumptions, we obtain consistent estimates

[3] Households often have more than one plot of each crop, but since the instrument (diffusion rate) takes on the same value, we cannot combine IV and FE for a single crop. For example, if a household has 2 maize plots, both plots have the same value for maize diffusion rate. Hence, if we use HH FE-IV, the instrument will drop out as it does not vary within the household. But when we combine crops, the instrument value varies within a household because different crops have different diffusion rates.

of β_1. The instrument will not be valid if it affects yields through mechanisms other than more fertilizer being applied on that plot. For example, it would be problematic if the instrument was to be correlated with more intensive use of other inputs. Since we include the quantity of other inputs allocated to the plot as explanatory variables, we overcome this problem by controlling for the effect the instrument might have through other inputs. We not cluster errors by household when using fixed effects models.

In the Sudan Savanna case study, which is a relatively small sample of households, all regressions are estimated with robust standard errors, clustered by household. In the regressions estimated with nutrients measured in laboratory tests on soil samples, we combine both dryland cereals in one regression given the even smaller number of observations. Binary and interaction variables are included to control for crop effects on grain yield and yield response to nitrogen nutrients per ha. We also test a quadratic term for nitrogen nutrients per ha, which expresses whether a turning point in yield response to nitrogen is observable in the data. In the set of regressions estimated with farmer-perceived soils classes, along with the combined regression, we have also estimated separate regressions for maize and sorghum because sample sizes are larger.

As a robustness check we also test the final combined model with farmer-perceived soil classes (the largest sample) with the Control Function Approach. A Control Function Approach is applied instead of instrumental variable methods because of the potential endogeneity of multiple variables (nitrogen fertilizer applied, interaction and squared terms). As instruments, we utilize both whether the plot manager has benefited from the fertilizer subsidy and the village share of plot managers who are members of registered cooperatives. In a recent study, Theriault, Smale, and Assima (forthcoming) found that Malian farmers who are members of cooperatives have better access to fertilizer than non-members. Participation in the subsidy program and cooperative is likely to affect fertilizer use (inclusion restriction) but unlikely to be correlated with unobservables (exclusion restriction).

2.3 Variables

Explanatory variables in the two analyses differ somewhat to reflect underlying differences in the data. Variables used in the LSMS analysis are listed in Table 1. The area of the plot, measured in hectares, allows us to examine whether productivity differs across plot sizes. In the LSMS data, our vector I includes a broad set of agricultural inputs: manure, compost, other organic fertilizer (i.e., crop residues), pesticides, herbicides, fungicides, other protecting liquids, improved and local seed. The distance of the plot from the homestead is related to the time taken to reach the field for crop management and is also, potentially, a measure of fertility since those located farther away may have been more recently cleared and brought into cultivation. Also, households may choose to invest more in nearby plots, since they are more secure (Gebremedhin and Swinton 2003) and easier to reach, reducing traveling time and cost. A dummy variable is also included to control for whether there is an anti-erosion structure on the plot, such as stone contour bunds or dikes—which have been promoted in certain regions of the country to offset the heavy loss of soil nutrients during the rainy season and enable farmers to retain moisture (Tappan and McGahuey 2007).

Location in the toposequence (lowland, plain, slope, plateau) and soil texture and important indicators of soil quality in this region and highly correlated with crop grown (Udry 1996; Guirkinger et al. 2015). Bazile et al. (2008) explains that farmers define soil type according to the position of the field in the toposequence. Farmers distinguish the shallow soils of the plateaus or higher areas from medium-depth soils and alluvial, low-lying soils ('bas-fonds'). Observed within and among farms, soil differentiation provided one explanation for growing multiple varieties and crops per farm and across a landscape. To capture the location of the plot in the toposequence, we include binary indicators of location in the plain, lowland, on a slope or plateau. Dummy variables for soil type are also included, representing farmer-perceived soil classes (sandy, silty, clayey).

Explanatory variables used in the analysis of the Sudan Savanna data are listed in Table 2. We estimate maize-sorghum yield (grain harvested per ha) response to nitrogen, but do not include millet plots, for which we do not have production data. Fertilizer application is computed in the same way as in the LSMS analysis, and all regressions include conventional inputs, a common set of plot characteristics, and a rainfall indicator at the village-level. Manure application is measured as a binary variable because of difficulties in measuring quantities reliably. Labor days, liters of herbicides, and hours of equipment use are computed per ha. Common plot characteristics are distance (in minutes walking) from the homestead to the plot, presence of a soil erosion structure on the plot, association of the primary crop with a leguminous (groundnut, cowpea) intercrop. Average rainfall during the period of fertilization in the survey year is recorded at the geographical scale of the village.

Two sets of plot soils characteristics are tested with the Sudan Savanna data. In the first, soils characteristics are by soil nutrient content as tested in the laboratory. These include the percentage soil organic matter (C), sand, silt and clay, the percentage total nitrogen (N), assimilable phosphorus (P), exchangeable potassium (K), and soil pH (KCI). Since total carbon content (C) changes over centuries and active carbon changes over a period of 3-5 years (Weil et al. 2016), these are not affected by recent applications of fertilizer. Similarly, total nitrogen content (N), which includes the nitrogen in the soil organic matter, is not affected by recent fertilizer use (Sieglinde Snapp, pers. comm., October 17, 2017). Nor can farmers deduce the specific nutrient content of their soils (P, K). In the second, we substitute farmer-perceived soils characteristics. Binary variables are entered for location of the plot in the toposequence and farmer-perceived soil classes, as in the LSMS data, although categories differ slightly.

3 Results

3.1 Descriptives

Millet, sorghum and maize are grown on 39, 32 and 29 percent of the plots in the LSMS sample, respectively. The distribution of the plots by region and crop is shown in Table 3. Only a handful of observations appear for Tombouctou, and Gao, with a few for peri-urban areas around Bamako. Millet plots are concentrated in the primary millet growing areas of Segou and Mopti, while sorghum is represented across primary and secondary sorghum-growing regions of Koulikoro, Segou, Kayes, and Sikasso. Maize is most heavily represented in Sikasso.

Fertilizer application rates differ significantly across crops. Table 4 shows average use rates calculated from the LSMS and Sudan Savanna datasets by cereal crop and region, compared with recommended rates and economically optimal rates estimated with response functions based on experimental data (Dicko et al. 2016). They also differ in major ways by region, as would be expected given regional locations relative to bioclimate.

Agronomic recommended rates of N per ha are 32 for sorghum and millet, and 84 for maize, throughout the country (Dicko et al. 2016). These correspond to 100 kg/ha on all three crops for cereal complex, 100 kg/ha of NPK (16-16-16) for millet and sorghum, 250 kg/ha of NPK (23-10-5) for maize, 100-150 of DAP on cereals, and 50-400 kg/ha for other crops and fertilizers (see also Thériault et al. 2016). The overall mean for N kg per ha on millet, sorghum and maize in the LSMS data is 6.7, but use rates on maize are considerably higher except for the region of Kayes. For all three cereals and all five regions except millet in Sikasso, estimated mean rates of use are but a fraction of economically optimal rates. In Koulikoro, Segou and Mopti, average N use rates on both sorghum and millet are in the single digits or lower, while economic optima range from 21 to 26. Again, the mean rate of N applied per ha to maize in Sikasso (36.2) is closest but is still far from the economic optimum (56-65). Mean phosphorus application rates for the entire LSMS sample are only 1 kg/ha and 1.9 kg/ha for millet and sorghum respectively, but 6.7 kg/ha for maize—which is close to recommended levels. Recommended use rates for P are 10 for sorghum and millet, and economically optimal rates are estimated to be higher (Dicko et al. 2016).

Overall, applying their fertilizer optimization tool, Dicko et al. (2016) found that the economically optimal rates of N were well below recommendations for maize, sorghum and millet, varying by bioclimate (Sahel, Sudan Savanna, Pre-Guinean). The opposite was generally true for P on sorghum and millet, but not on maize. Response to P was especially strong in the drier areas. Previous research by Doumbia et al. (1993) and current research by Rattunde et al. (forthcoming) report the effects of low assimilable P on sorghum in particular.

Mean applications rates of N per hectare on maize and sorghum are also shown in Table 4 for the Sudan Savanna. In this relatively high potential area, mean rates of use on sorghum (6.41) are closer to rates in Sikasso in the LSMS (9.38) than in Koulikoro at (<1), and even roughly the same on maize (39.8) as in Sikasso (36.2). Again, both of these are but a fraction of the economically optimal rate estimated by Dicko et al. (2016), which is, in turn, but a fraction of the nationally recommended rate.

3.2 Yield response functions

Tables 5-8 present yield response models estimated with the LSMS data. The yield and input variables, including the quantity of fertilizer, are included in logarithms4, in order to smoothen their distributions, which are concentrated in lower values and skewed in shape. Hence, β_1 and $\boldsymbol{\beta_2}$ will be interpreted in terms of percentage changes of yield. For example, a one percent increase in the quantity of fertilizer applied to a plot results in a β_1 percent increase in the dry-land cereal crop yield. The coefficients have been converted into marginal products by computing the marginal change in yield (in kg/ha) from a one percent increase in the quantity of fertilizer (N kg/ha) at the mean, and are indicated in the bottom rows of the tables. The models were also estimated in levels form (without taking the logarithm of yield or inputs) and provides similar estimates, but the coefficients are less precisely estimated. The estimates from the levels specification are shown in the appendix.

We first quantify the effect of nitrogen nutrients on crop yields using household fixed effects estimation (Table 5). All regressions are estimated at the plot level. The dependent variable is crop yield (kg/ha), and dummy variables are included to control for dryland cereal. Other control variables described above are included sequentially to see whether the coefficient on fertilizer changes substantially.

The coefficients on nitrogen fertilizer across the models suggest that a one percent increase in the quantity of nitrogen fertilizer applied to the plot results in 0.04-0.07 percent increase in yields of dryland cereal crops. While the coefficient is statistically greater than zero at at least the ten percent significance level in all specifications, results indicate a relatively low yield response to nitrogen. These elasticities correspond to marginal physical products of 5.2 to 8.85, on average, for dryland cereals (maize, millet and sorghum).

We find that yields are decreasing in plot size – consistent with the inverse productivity relationship (Benjamin 1995) that has also been observed in this region (Udry 1996; Kazianga and Wahhaj 2013; Guirkinger et al. 2015). Plots where manure has been applied, and those with anti-erosion structures, achieve greater yields. Yields are increasing in the quantity of local seed, and increasing even more in the quantity of improved seeds. More labor allocated to a plot also raises yields. This effect is strong throughout and with a relatively high elasticity (0.3-0.4)—suggesting that labor constrains productivity. There is some evidence that herbicide use improves yields by protecting crops, but not in the more complete models (5). Pesticide use (more likely

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[4] Since the variables can take on zero values, one is added to them before taking the natural logarithm

[5] These figures are calculated by multiplying the estimated coefficients by the average yield and fertilizer quantities of the regression sample

on maize than the other crops) affects yields positively, but we find no effects of fungicides, or other protecting liquids, which are used in very limited amounts. Presence of anti-erosion structures has a meaningful and significant effect on yields.

Next, we turn to the FE-IV estimates for more robust inference on the effect of fertilizer on yields (Table 6). In all specifications, the first-stage F-statistic is much greater than 10, which is often used as a rule of thumb for the inclusion restriction. The first-stage F-statistic is also greater than the Stock-Yogo 10 percent maximal IV size critical value of 16.38, suggesting that the inclusion restriction is satisfied. The FE-IV estimates for fertilizer are several times as large as those shown in Table 5, suggesting that endogeneity may diminish estimates of the yield response to fertilizer. In all specifications, the effect of nitrogen fertilizer applied is statistically significant. A one percent increase in the quantity of fertilizer applied to the plot results in 0.1-0.2 percent increase in yields of dryland cereal crops. This translates to a 17-27 kg/ha increase in dryland cereal crop yield for an additional nitrogen kg/ha of fertilizer. Controlling for toposequence and soil type, in particular, reduces the marginal product attributable to fertilizer.

Both models presented in Tables 5 and 6 were also estimated with specifications that contained square terms for fertilizer and interaction terms between fertilizer and crop dummy variables. The point estimates of these square and interaction terms were close to zero and not statistically significant; hence, we selected more parsimonious specifications.

Separate household fixed effects regressions have also been estimated for each cereal crop (Tables 7-9). Since the instrument does not vary across plots growing the same crop within a household, there are no FE-IV estimators for the models when estimated separately by crop. The results suggest that millet and sorghum yields are unaffected by fertilizer use. For maize, in one of the simpler models, a one percent increase in the quantity of fertilizer applied to the plot results in about 0.15 percent higher in yields, corresponding to a marginal product of 11. These models have a smaller sample size than the pooled household fixed effects models shown in Table 6, leading to less precise estimates. Additionally, these coefficients may be downward biased, given that the estimates from the pooled household fixed effects models are smaller than the FE-IV estimates. However, we may consider these estimates as lower bounds for the true effect of fertilizer on crop yields.

Overall, analysis of the LSMS data demonstrates that nitrogen fertilizer has positive and statistically significant effects on yields of dryland cereals. Although the estimates generated with OLS are close to zero in magnitude, when we account for endogeneity of fertilizer use, predicted magnitudes rise the range of 17-23 for the three crops combined. For maize in particular, these fall within the expected range. Ahmed, Gautam and Gaskell (2017), who employed a stochastic function approach using the same dataset, found no statistically significant effects of mineral fertilizer on crop yield. Foltz, Aldana and Laris (2012) estimated significant maize yield elasticities of 0.2-0.3 for fertilizer—higher than what we found here, although they used total fertilizer kg and utilized data only from the highly productive region of Sikasso.

Suggested by the sample distribution reported in Table 3, one explanation for weak results could be that national representation in the sample spans enormous differences in farming systems and agroecologies, so that representation of any particular farming system is inadequate.

This is one reason why we include estimates from the Sudan Savanna case study. The Sudan Savanna has the greatest agricultural potential in Mali for production of both sorghum and maize (Dicko et al. 2016). Despite this, anecdotally, farmers surveyed reported sorghum yields were lower than they expected due to declining soil fertility, but also moisture and pest damage—giving them incentives to switch from sorghum to maize (Alpha Kergna, pers. comm.). Even here, the data indicate a very modest yield response rate to fertilizer for either crop. One reason why, in sorghum, could be the extremely low rate of application—application rates per ha on maize plots in our survey averaged 158 kg total of fertilizer, or 39.8 N nutrients/ha, compared with only 27 total kg of fertilizer on sorghum (6.4 N nutrients/ha). On sorghum, however, this mean is higher than in the LSMS data. There are a large number of zeros in our sample for sorghum (66%), compared with only 14% on maize plots. Tables 10 and 11 provide additional insights.

Three response function specifications are shown in Table 10, each including soils characteristics measured in laboratory tests on samples. Model 1 is a simple linear regression, with sorghum plot entered only as a binary variable affecting overall yields. The effect on yield is strong and negative, reduce average grain yields by about 600 kg/ha relative to maize, controlling for other factors. Model 2 includes an interaction effect between N nutrient kg/ha and sorghum plot. The effect is negative but not statistically significant. In Model 3, the squared term is added for N applied and is negative in sign but not statistically significant. The interaction effect becomes significant, indicating that growing sorghum reduced yield response by 9 N nutrient kg/ha relative to maize. On average, Model 3 suggests that an additional kg of N nutrients per ha contributes an additional 10.4 kg of maize grain per ha. Combined with the interaction effect, this suggests a response rate of only about 1.3 for sorghum.

Other coefficients of interest, which are consistent across the three specifications, include a positive and significant effect of labor and equipment use, and a negative and significant effect of distance to the plot and legume intercrop on yields. The magnitudes and significance of the input effects suggest that these may constrain productivity, and this is supported by the negative effect on time walking to the plot from the homestead. The inverse relationship between yield and the legume intercrop is explained by the fact that we were unable to control for the area planted to primary and secondary crops—leading to a downward bias in the yield of the primary crop. On the other hand, any long-term, positive effects of intercropping would be difficult to discern in a single year's survey data of this type. Similarly, erosion structures were often constructed in earlier years, and may not be in good repair. Most are stone contour lines to control for erosion on slopes, but most of the plots in the sample are on the plain. Insignificance of the manure variable may reflect the fact that while most farmers apply manure (64%), there is considerable variation in the quantity and quality applied.

Among measured soil nutrients, the effect of P is strongly significant (at 1%), suggesting that it poses a constraint to productivity. In many of Mali's sorghum-growing areas, we have reason to believe that phosphorus is a more binding constraint than N (Kihara et al. 2016; Dicko et al. 2016; Weltzien, Pers.comm. November 29, 2017). Clay content is positively associated with productivity.

Table 11 presents the results of the Model 3 specification (crop binary variable, interaction of crop and N nutrient kg/ha, squared N nutrient kg/ha) for maize and sorghum combined, followed by regressions estimated separately by crop. The combined Model 3 results are similar to those shown in Table 7, both in terms of response magnitudes and significance and in terms of other main inputs (labor, equipment) influencing productivity. In the separate regressions, we find a significant yield response rate for maize of 14.4, and an insignificant response rate of 3.6 for sorghum.

Some differences appear in key factors across the regressions reported in Table 10. Soil erosion structure appears significant in the combined and sorghum-only regressions, with the expected positive sign. None of the maize plots was intercropped. Sandy soil type is weakly significant (10%) relative to gravelly soils in the combined regression. None of the three toposequence categories is significant in any of the regressions. Clayey soil type appears to be more important in the pooled and especially the sorghum regression, while use of manure is significant in the maize regression. Rainfall during the period of fertilization has a positive effect on productivity in the maize regression, but a negative effect in the sorghum regression. This may represent differences in moisture needs of the two crops relative to the growing season and soil moisture. Overall, the maize regression is statistically the weaker of the two, with far fewer observations than the sorghum regression.

Table 12 shows the coefficients from the second stage, yield response function estimated with the Control Function Approach. The yield regression is based on the combined maize-sorghum model with farmer-perceived soils classes, in order to benefit from as many observations as possible. In the first-stage regression, which tests and controls for potential endogeneity of fertilizer use in yield response, both the coefficient on the binary variable indicating that the plot manager benefited from the fertilizer subsidy, and the coefficient on the village proportion of plot managers who belong to a registered cooperative, are statistically significant at the 1% level. So too is the residual entered in the yield regression, failing to support exogeneity of fertilizer use in the yield response function. As was true in the LSMS estimates, marginal products of nitrogen fertilizer rise (24 for maize and 18 for sorghum) when endogeneity is taken into account.

The estimated response rates for maize reported in Tables 11 and 12 fall within the range of other estimates for the same crop based on data collected from farmers' fields in Sub-Saharan Africa. A review conducted by Yanggen et al. (1998) shows estimated response rates of maize to nitrogen to be generally lower in West Africa than in East and Southern Africa, with most in the 10-15 range. Based on nationally-representative cross-sectional and panel datasets, Koussoubé and Nauges (2017) and Theriault, Smale, and Haider (2017) estimated a yield response rate of about 19 kg/ha to nitrogen on maize in Burkina Faso, respectively. By contrast, Marenya and Barrett (2009) estimated a marginal product of 40-44 kg/ha in Western Kenya, while Sheahan et al. (2013) reported marginal products ranging from 14 to 25 kg/ha across the agro-ecologies of

Kenya. Response rates reported by Xu et al. (2009) for Zambia varied from under 10 to 30 kg/ha, with a median of 16.

Estimates of sorghum yield response to fertilizer, though low and statistically insignificant, are also within the range cited in the literature. Analysis of trial data by Institut de Recherches Agronomiques Tropicales (IRAT) from 1978-82 in Burkina Faso showed experimental responses of 10.3 kg grain of sorghum per N nutrient kg, with much lower figures measured in farmers' fields (Matlon 1983). In an early review of literature on this topic, Yanggen et al. (1998) found that the marginal physical product of nitrogen nutrients in sorghum production was similar in Sub-Saharan Africa to other regions of the sorghum-producing world such as India, but were lower in West Africa, were most reported rates were in the 4-5 range. In a recent analysis conducted in Nigeria, Omonona et al. (2016) found response rates of only around 1 kg of sorghum in cereal root crop and agro-pastoralist farming systems.

4 Conclusions

In Mali, raising the production of dryland cereals (maize, millet, sorghum) in order to improve food security must be achieved through higher yields rather than further extension of cultivated area. Although maize yields on farms have increased in recent years, they are far below their potential. Generally, millet and sorghum yields on farms have remained low. Inadequate use of inorganic fertilizer has been pinpointed as a cause to low agricultural productivity in these crops. To encourage fertilizer use, and spur productivity, the Malian government has implemented a fertilizer subsidy program since the global food price crisis in 2008. Beginning in rice, the program now also targets dryland cereals. Yet, little is documented about the responsiveness of those crops to fertilizer under farmer's conditions. This study aims to fill this gap by examining dryland cereal yield responses to fertilizer using two farm household datasets. The first, the LSMS-ISA, is nationally-representative. The second, collected in the Sudan Savanna region, is representative of a relative high potential zone for sorghum and maize production.

A combination of econometric techniques is employed to control for potential endogeneity issues and check the robustness of the results. Four key findings emerge. First, it is important to control for endogeneity to avoid underestimating the effect of fertilizer use on yields. Second, soil texture and practices (anti-erosion structures) affect both yields and estimated effects of fertilizer. Third, sorghum yields have a lower response to fertilizer than maize yields. Fourth, dryland cereal yield responses to fertilizer are stronger in the Sudan Savanna region (sample) than nationwide (nationally-representative dataset), highlighting the importance of agroecological factors and farming systems. Together, these findings suggest that use of mineral fertilizer does have the potential to boost productivity, especially for maize, but in complementarity with other practices that reduce soil erosion and improve soil quality.

One key aspect that this study has not addressed is the profitability of fertilizer use. Related work by Dicko et al. (2016), which supports the need for varied recommendations, also suggests that economic optima are generally lower than agronomic optima recommended by national programs. Given that maize yields do respond to fertilizer use, can inadequate application rates be explained by low economic incentives? Does the subsidy program contribute to enhancing economic incentives? If so, at what social costs? Given the low response rates of millet and sorghum yields to fertilizer, does it make sense to provide them with subsidized fertilizer? Is it profitable to apply fertilizer, even at subsidized prices, on sorghum and millet? Further research is needed to tackle those important questions and make sound policy recommendations on the subsidy program itself and other mechanisms to promote agricultural intensification.

Figure 1a. Agro-ecological zones and regional capitals of Mali. The Sudan Savanna refers to the area spanning the 700-1000 mm isohyet (expected rainfall per year)

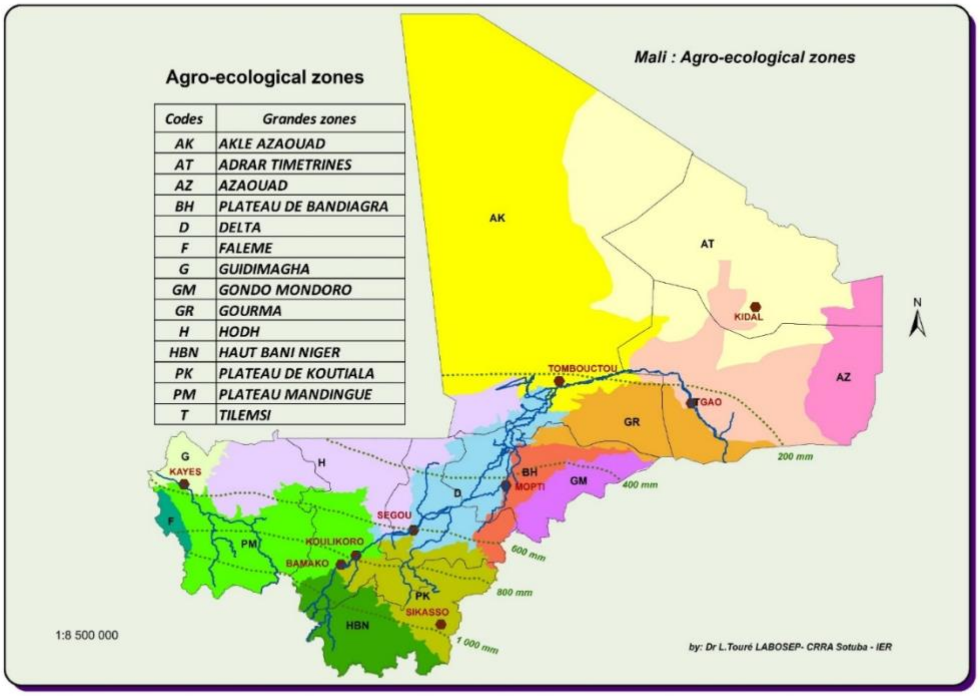

Figure 1b. Survey villages in Sudan Savanna, agro-ecological zones and 800 mm isohyet

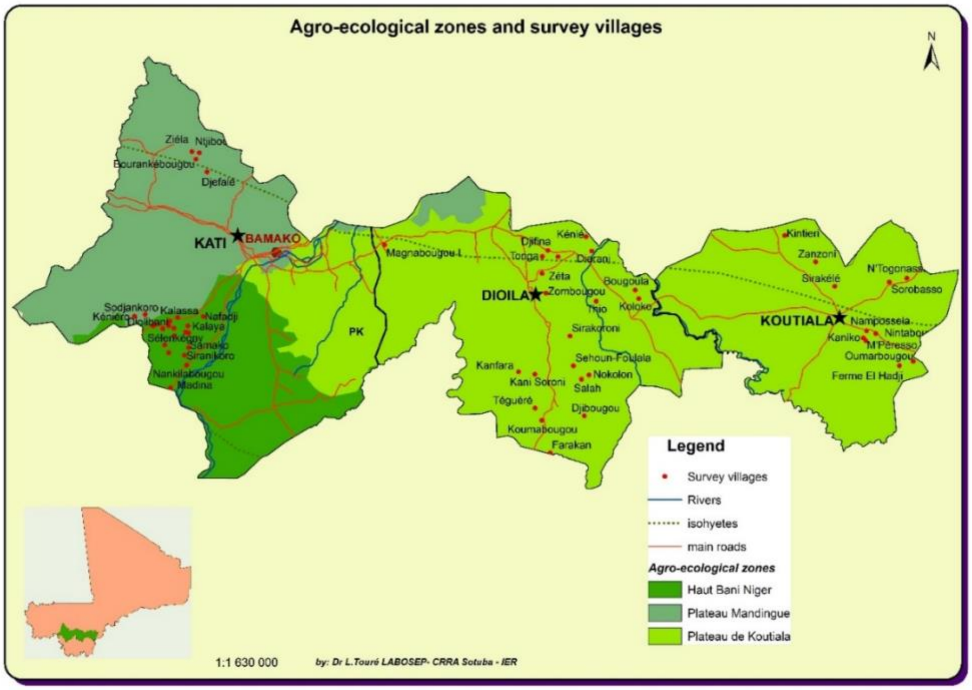

Table 1: Descriptive statistics, LSMS-ISA data

Variable	Mean	S.D.	Min	Max
Millet Yield (kg/ha)	695.82	629.85	0.66	3759.40
Sorghum Yield (kg/ha)	735.70	686.50	0.53	3930.13
Maize Yield (kg/ha)	1492.66	1221.45	1.26	6000
Material Inputs				
Nitrogen Fertilizer (N nutrient kg/ha)	6.74	23.60	0.00	288.66
Manure (kg/ha)	1594.88	3800.28	0.00	29850.75
Compost (kg/ha)	25.84	247.22	0.00	4889.98
Other Organic Fertilizer (kg/ha)	5.64	60.61	0.00	1708.43
Pesticides (liter/ha)	0.053	0.51	0.00	10.47
Fungicide (liter/ha)	0.033	0.42	0.00	19.66
Herbicide (liter/ha)	0.27	1.17	0.00	19.05
Other Protecting Liquids (liter/ha)	0.0066	0.11	0.00	3.14
Local Seed (kg/ha)	10.37	15.42	0.00	236.84
Improved Seed (kg/ha)	1.00	4.45	0.00	50.72
Labor				
Total Labor (no. of days/ha)	45.13	84.84	0.00	1031.25
Plot Characteristicss				
Plot Area (ha)	3.07	6.12	0.02	52.73
Distance to plot from house (km)	2.81	4.00	0.00	60.00
Plain (0/1)	0.70	0.46	0.00	1.00
Plateau (0/1)	0.14	0.35	0.00	1.00
Lowlands (0/1)	0.034	0.18	0.00	1.00
Sloped (0/1)	0.13	0.34	0.00	1.00
Soil Sandy (0/1)	0.53	0.50	0.00	1.00
Soil Clay (0/1)	0.36	0.48	0.00	1.00
Soil Lateritic (0/1)	0.11	0.31	0.00	1.00
Anti-Erosion Structure (0/1)	0.043	0.20	0.00	1.00

Source: Authors, based on LSMS-ISA, Mali. Number of plot observations=3733

Table 2. Descriptive statistics, Sudan Savanna data

Variable	Mean	S.D.	Min	Max
Maize yield (kg/ha)	1497	945	12.5	4730
Sorghum yield (kg/ha)	642	681	0	4286
Nitrogen fertilizer (nutrient kg/ha)	19.5	25.7	0	100
Sorghum plot (0/1)	0.609	0.488	0	1
Manure (0/1)	0.641	0.479	0	1
Labor (days/ha)	67.98	66.56	0	800
Herbicide (liters/ha)	1.68	2.24	0	25.0
Equipment (hours/ha)	475	474	0	5294
Distance from House (minutes)	17.43	17.48	1	160
Soil Erosion Structure	0.188	0.391	0	1.00
Legume Intercrop 0/1)	0.112	0.316	0	1.00
N (% total nitrogen)	0.028	0.023	0.010	0.200
C (% organic matter)	0.522	0.334	0.020	2.63
P (assimilable phosphorus)	1.29	1.31	0.210	15.9
K (exchangeable K)	0.246	0.210	0.020	1.87
Ph (KCI)	5.34	0.40	3.15	7.25
Sand (% > 0.05)	59.6	12.8	7	90.0
Silt (%0.05-0.002 mm)	36.2	12.3	8	90.0
Clay (% < 0.002 mm)	4.26	2.88	0	23.0
Rainfall (mm, period of fertilization)	220	31	164	299
Plain	0.865	0.341	0	1
Lowlands	0.015	0.122	0	1
Slope	0.119	0.324	0	1
Sandy (0/1)	0.381	0.486	0	1
Silty (0/10	0.203	0.403	0	1
Clayey (0/1)	0.269	0.444	0	1
Gravelly (0/1)	0.147	0.354	0	1

Source: Authors, based on Sudan Savanna case study data. n=1222 for all except manure (1096).

Table 3. Distribution of LSMS analytical sample by region and crop

Region	Millet		Sorghum		Maize	
	n	%	n	%	n	%
Kayes	62	3.40	375	25.76	294	21.91
Koulikoro	359	19.68	378	25.96	276	20.57
Sikasso	190	10.42	281	19.30	616	45.90
Segou	623	34.16	346	23.76	142	10.58
Mopti	516	28.29	68	4.67	0	0.00
All	1750	100	1448	100	1328	100

Source: Authors, based on LSMS data.

Table 4. Average use rates for N, compared with recommended and economic optima, by region and crop

	Average use rates (N kg/ha)	Economically optimal rate	Recommended rate
LSMS-ISA			
		Millet	
Kayes	0.000	no data	32
Koulikoro	0.316	no data	32
Sikasso	8.19	8	32
Segou	3.65	21	32
Mopti	1.50	21	32
		Sorghum	
Kayes	0.182	26	32
Koulikoro	0.722	26	32
Sikasso	9.38	26-28	32
Segou	7.15	20-26	32
		Maize	
Mopti	0.360	20	32
Kayes	0.453	54	84
Koulikoro	17.3	54	84
Sikasso	36.2	54-65	84
Segou	11.7	31-54	84
Sudan Savanna			
		Sorghum	
Koulikoro, Sikasso	6.41	26	32
		Maize	
Koulikoro, Sikasso	39.8	54	84

Source: Authors, based on LSMS and Sudan Savanna survey data; recommended and economically optimal rates from Dicko et al. (2016).

Notes: Tombouctou, Gao and Mopti (for maize) excluded because of very few observations.

Table 5: Dryland cereals yield response to N fertilizer applied, household fixed effects model

Variables	(1)	(2)	(3)	(4)
Nitrogen Fertilizer	0.0688***	0.0654***	0.0420*	0.0506*
	(0.0227)	(0.0243)	(0.0238)	(0.0258)
Manure		0.0309***	0.0310***	0.0318***
		(0.00756)	(0.00784)	(0.00877)
Compost		-0.0338	-0.0274	-0.0188
		(0.0342)	(0.0331)	(0.0367)
Other Organic		0.0483	0.0189	0.0128
		(0.0565)	(0.0564)	(0.0569)
Pesticide		0.272	0.363*	0.528**
		(0.198)	(0.193)	(0.261)
Fungicide		0.227	0.147	0.164
		(0.252)	(0.235)	(0.249)
Herbicide		0.253**	0.0637	0.0231
		(0.118)	(0.124)	(0.135)
Other Protecting		0.978	1.222	1.583
		(1.164)	(1.081)	(1.115)
Total Labor		0.440***	0.327***	0.270***
		(0.0277)	(0.0305)	(0.0366)
Local Seed			0.359***	0.311***
			(0.0360)	(0.0411)
Improved Seed			0.502***	0.445***
			(0.0685)	(0.0794)
Millet	-0.325***	-0.0236	0.137**	0.200**
	(0.0593)	(0.0641)	(0.0674)	(0.0787)
Sorghum	-0.486***	-0.251***	-0.0969*	-0.0196
	(0.0505)	(0.0546)	(0.0572)	(0.0686)
Plot Area				-0.0249***
				(0.00488)
Distance to plot				0.0177*
				(0.00905)
Plain				0.0353
				(0.126)
Plateau				0.00978
				(0.163)
Lowland				0.140
				(0.189)
Sandy				-0.0609
				(0.193)
Clay				-0.0344
				(0.197)
Anti-Erosion				0.488**
				(0.199)
Constant	6.425***	4.778***	4.244***	4.490***
	(0.0459)	(0.102)	(0.114)	(0.235)
Observations	3,327	2,840	2,346	1,834
Number of households	1,374	1,264	1,033	824
Marginal Effect of N Nutrient Applied	8.82	8.33	5.15	

Source: Authors, based on LSMS data. Standard errors in parentheses. Sample sizes drop with missing observations in more complete models, particularly those including seed quantities. *** p<0.01, ** p<0.05, * p<0.1

Table 6. Dryland cereals yield response to N fertilizer applied, instrumental variables-household fixed effects model

Variables	(1)	(2)	(3)	(4)
Nitrogen Fertilizer	0.190***	0.218***	0.162**	0.149*
	(0.073)	(0.081)	(0.075)	(0.080)
Manure		0.026***	0.024**	0.026***
		(0.008)	(0.009)	(0.010)
Compost		-0.058	-0.044	-0.033
		(0.038)	(0.037)	(0.041)
Other Organic Fertilizer		0.051	0.024	0.022
		(0.066)	(0.066)	(0.067)
Pesticide		0.253	0.304	0.304
		(0.211)	(0.201)	(0.280)
Fungicide		0.076	0.029	0.082
		(0.272)	(0.248)	(0.259)
Herbicide		0.104	-0.063	-0.095
		(0.137)	(0.134)	(0.144)
Other Protecting Liquids		0.673	0.769	0.967
		(1.285)	(1.178)	(1.202)
Total Labor		0.447***	0.335**	0.283***
		(0.030)	(0.033)	(0.039)
Local Seed			0.353**	0.294***
			(0.039)	(0.044)
Improved Seed			0.488**	0.417***
			(0.073)	(0.085)
Millet	-0.159*	0.071	0.249**	0.295**
	(0.090)	(0.093)	(0.096)	(0.117)
Sorghum	-0.393***	-0.188**	-0.036	0.053
	(0.075)	(0.077)	(0.079)	(0.101)
Plot Area				-0.025***
				(0.005)
Distance (km) from House				0.017*
				(0.009)
Plain				-0.008
				(0.130)
Plateau				-0.019
				(0.170)
Lowland				-0.005
				(0.210)
Sandy				-0.032
				(0.210)
Clay				-0.028
				(0.212)
Anti-Erosion Structure				0.486**
				(0.198)
Observations	2,453	2,043	1,707	1,307
Number of households	776	671	548	425
Kleibergen Paap F statistic	218.6	155.8	148.3	112.5
Marginal Effect of N Nutrient Applied	23.13	26.95	19.49	16.81

Source: Authors, based on LSMS data. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Sample sizes drop with missing observations in more complete models, particularly those including seed quantities.

Table 7: Millet yield response to N fertilizer applied, household fixed effects model

Variables	(1)	(2)	(3)	(4)
Nitrogen Fertilizer	0.0392	-0.00945	0.00449	-0.00372
	(0.0724)	(0.0685)	(0.0642)	(0.0714)
Manure		0.0271**	0.0222*	0.0156
		(0.0122)	(0.0122)	(0.0137)
Compost		-0.0774	-0.0518	-0.0751
		(0.0754)	(0.0744)	(0.0862)
Other Organic		0.0832	0.0806	0.0803
		(0.0720)	(0.0676)	(0.0657)
Fungicide		-0.668	-0.630	-1.261
		(1.004)	(0.938)	(0.923)
Herbicide		2.565	0.960	2.138
		(10.59)	(9.893)	(9.408)
Total Labor		0.470***	0.314***	0.156***
		(0.0481)	(0.0529)	(0.0602)
Local Seed			0.409***	0.360***
			(0.0652)	(0.0698)
Improved Seed			0.550***	0.350
			(0.208)	(0.259)
Plot Area				-0.0310***
				(0.00828)
Distance to plot				0.0334**
				(0.0150)
Plaine				0.0543
				(0.186)
Plateau				0.0202
				(0.314)
Lowland				-0.220
				(0.383)
Sandy				-0.00658
				(0.411)
Clay				0.411
				(0.448)
Anti-Erosion				1.789***
				(0.369)
Constant	5.996***	4.633***	4.267***	4.635***
	(0.0282)	(0.139)	(0.150)	(0.466)
Observations	1,376	1,182	1,018	813
Number of	771	688	585	476
Marginal Effect of Nutrient Applied	10.37	-2.34	0.99	-0.81

Source: Authors, based on LSMS data. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Sample sizes drop with missing observations in more complete models, particularly those including seed quantities.

Table 8: Sorghum yield response to N fertilizer applied, household fixed effects model

Variables	(1)	(2)	(3)	(4)
Nitrogen Fertilizer	0.0503	0.0663	0.0265	0.0399
	(0.0590)	(0.0545)	(0.0582)	(0.0579)
Manure		0.0356	0.0411*	0.0301
		(0.0220)	(0.0245)	(0.0250)
Compost		-0.184	0.432	4.949
		(0.441)	(1.146)	(5.166)
Other Organic Fertilizer		-1.010	-1.025	-0.910
		(1.889)	(1.878)	(1.724)
Fungicide		2.347**	2.081*	4.539***
		(1.168)	(1.157)	(1.726)
Herbicide		0.0986	0.0539	0.0319
		(0.281)	(0.310)	(0.295)
Total Labor		0.496***	0.316***	0.309***
		(0.0567)	(0.0704)	(0.0761)
Local Seed			0.269***	0.264***
			(0.0828)	(0.0864)
Improved Seed			0.655***	0.444**
			(0.202)	(0.213)
Pesticide		-0.727	-3.386	-23.47
		(1.605)	(5.036)	(23.03)
Plot Area				-0.00449
				(0.00972)
Distance to plot				-0.0140
				(0.0151)
Plaine				-0.0652
				(0.250)
Plateau				-0.291
				(0.388)
Lowland				0.0337
				(0.310)
Sandy				-0.325
				(0.432)
Clay				-0.456
				(0.401)
Anti-Erosion Structure				-0.171
				(0.441)
Constant	5.961***	4.389***	4.351***	4.985***
	(0.0297)	(0.175)	(0.202)	(0.462)
Observations	1,170	1,001	816	664
Number of households	767	666	534	445
Marginal Effect of N Nutrient Applied	9.56	11.70	4.73	6.44

Source: Authors, based on LSMS data. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Sample sizes drop with missing observations in more complete models, particularly those including seed quantities.

Table 9: Maize yield response to N fertilizer applied, household fixed effects model

Variables	(1)	(2)	(3)	(4)
Nitrogen Fertilizer	0.0658	0.146**	0.000670	-0.0620
	(0.0541)	(0.0676)	(0.0638)	(0.0747)
Manure		0.00286	0.00169	0.0125
		(0.0268)	(0.0237)	(0.0275)
Compost		-0.0796	-0.0520	-0.0646
		(0.0639)	(0.0585)	(0.0755)
Other Organic		0.218	0.435*	0.420
		(0.147)	(0.231)	(0.290)
Fungicide		-0.0489	-0.367	0.0470
		(0.509)	(0.442)	(1.038)
Herbicide		-0.0469	-0.236	0.129
		(0.226)	(0.276)	(0.329)
Total Labor		0.540***	0.403***	0.443***
		(0.0786)	(0.0849)	(0.111)
Local Seed			0.662***	0.706***
			(0.114)	(0.186)
Improved Seed			0.719***	0.572***
			(0.133)	(0.182)
Pesticide		0.366	0.459	-0.242
		(0.290)	(0.291)	(0.669)
Other Protecting		0.887	0.891	-0.176
		(1.170)	(1.014)	(1.168)
Plot Area				-0.0541***
				(0.0147)
Distance to plot				0.0902
				(0.0768)
Plain				0.0520
				(0.590)
Plateau				-0.564*
				(0.335)
Lowland				1.806*
				(0.923)
Sandy				0.368
				(0.589)
Clay				-0.207
				(0.627)
Anti-Erosion Structure				1.016*
				(0.514)
Constant	6.603***	4.623***	3.614***	3.386***
	(0.0787)	(0.260)	(0.319)	(0.710)
Observations	781	657	512	357
Number of households	559	481	369	264
Marginal Effect of N Nutrient Applied	5.01	11.33	0.049	-3.83

Source: Authors, based on LSMS data. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Sample sizes drop with missing observations in more complete models, particularly those including seed quantities.

Table 10. Maize-sorghum yield response including measured soil nutrients, Sudan Savanna

	(1) linear	(2) interaction	(3) quadratic and interaction
N nutrients/ha	2.864	4.356	10.42*
	(1.974)	(2.646)	(5.543)
Sorghum plot	-596.8***	-502.7***	-351.7*
	(131.5)	(156.6)	(197.8)
Sorghum plot x N nutrients/ha		-5.593	-9.134*
		(3.576)	(4.669)
$(N\ nutrients/ha)^2$			-0.0381
			(0.0300)
Manure	80.40	73.30	83.28
	(117.1)	(117.4)	(117.9)
Labor	3.099***	3.051***	3.155***
	(1.020)	(1.015)	(1.013)
Herbicides	15.05	17.00	18.11
	(27.43)	(27.46)	(27.03)
Equipment	0.721***	0.724***	0.724***
	(0.153)	(0.153)	(0.152)
Distance to plot	-3.374*	-3.338*	-3.343*
	(1.744)	(1.732)	(1.731)
Soil erosion structure	-78.13	-81.10	-82.52
	(100.8)	(101.7)	(103.3)
Legume intercrop	-238.8***	-233.1***	-236.5***
	(88.85)	(86.80)	(85.86)
lnN	-90.00	-94.77	-81.98
	(71.55)	(70.75)	(69.99)
lnC	-92.00	-84.60	-89.99
	(61.40)	(62.12)	(61.85)
lnP	137.2***	146.6***	149.7***
	(47.61)	(47.33)	(47.14)
lnK	-58.34	-65.67	-61.44
	(65.13)	(66.11)	(65.56)
lnPh(kcl)	191.6	150.2	286.6
	(430.7)	(436.8)	(434.8)
Sand	14.18	15.36	14.66
	(17.97)	(18.41)	(18.48)
Silt	17.07	17.93	17.23
	(18.35)	(18.76)	(18.82)
Clay	60.80**	63.77**	62.86**
	(27.67)	(28.17)	(28.01)
Rainfall	-0.552	-0.306	-0.0562
	(1.339)	(1.335)	(1.363)

Constant	-1,707	-1,891	-2,230
	(2,235)	(2,279)	(2,305)
Observations (n plots)	643	643	643
R-squared	0.518	0.520	0.523

Source: Authors, based on Sudan Savanna data. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 11. Maize-sorghum yield response including farmer-perceived soil types, Sudan Savanna

	(1) Combined	(2) Maize	(3) Sorghum
N nutrients/ha	10.52**	14.43***	3.634
	(4.501)	(5.427)	(4.065)
Sorghum plot	-273.1**		
	(112.1)		
Sorghum plot x N nutrients/ha	-6.608**		
	(3.238)		
(N nutrients/ha)^2	-0.0102	-0.0471	-0.00551
	(0.0454)	(0.0569)	(0.0653)
Manure	89.49	229.4**	-43.94
	(58.60)	(90.18)	(68.72)
Labor	2.184***	4.015***	1.802**
	(0.693)	(1.084)	(0.800)
Herbicides	-0.835	-7.904	4.472
	(14.89)	(26.35)	(16.08)
Equipment	0.391***	-0.0169	0.541***
	(0.103)	(0.182)	(0.0723)
Distance to plot	-1.344	-1.193	-2.053*
	(1.656)	(4.444)	(1.099)
Soil erosion structure	161.5**	195.8	149.0**
	(71.43)	(120.4)	(75.23)
Legume intercrop	-386.8***		-320.8***
	(54.41)		(56.26)
Plain	-65.03	-10.85	3.302
	(127.2)	(158.1)	(81.89)
Lowland		-67.34	144.9
		(504.9)	(150.9)
Slope	-63.54		
	(152.2)		
Sandy	137.2*	-27.07	77.60
	(74.00)	(119.0)	(52.43)
Silty	114.8		
	(78.54)		
Clayey	149.8*	-159.2	168.2**
	(81.99)	(123.7)	(78.65)
Gravelly		-176.5	-80.07
		(159.3)	(68.94)
Rainfall	0.447	3.576**	-1.603*
	(0.936)	(1.657)	(0.911)
Constant	402.2	-404.1	666.5***
	(262.3)	(456.5)	(251.1)

Observations	1,086	421	665
R-squared	0.410	0.198	0.387

Source: Authors, based on Sudan Savanna data. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 12. Maize-sorghum yield response to nitrogen applied, Control Function Approach

	(1)
Nitrogen fertilizer	23.98***
	(5.035)
Residual, stage 1	-16.33***
	(3.916)
Sorghum plot	622.1***
	(236.6)
Sorghum plot x N nutrients/ha	-5.565*
	(3.110)
(N nutrients/ha)^2	0.00795
	(0.0439)
Manure	180.7***
	(60.61)
Labor	3.365***
	(0.777)
Herbicides	-3.601
	(15.01)
Equipment	0.351***
	(0.101)
Distance to plot	-3.118*
	(1.816)
Soil erosion structure	115.5
	(70.55)
Legume intercrop	-524.4***
	(65.38)
Plain	-100.5
	(119.9)
Slope	-120.4
	(144.2)
Sandy	-10.72
	(76.59)
Silty	35.67
	(80.92)
Clayey	173.7**
	(77.86)
Rainfall	-0.540
	(0.979)
Constant	-18.04
	(262.7)
Observations	1,086
R-squared	0.424

Source: Authors, based on Sudan Savanna data. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

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Appendix 1: LSMS data cleaning

Plot areas (ha) were measured using GPS coordinates. These are more continuous and potentially more reliable estimates than the self-reported values, which have pile-ups at integer (and other) values (see Appendix Figure 1). GPS coordinates were collected from most (97 percent) plots, so using them does not lead to more missing values or a smaller sample size. Since the analysis is highly sensitive to outliers, we trim the smallest and largest 1 percent plots.

The quantity for different types of fertilizer was reported in standard units (kg or sacks) and non-standard units (donkey cart and ox cart). We considered that reports of carts referred to transport rather than actual quantities. Applying recommended conversions for carts led to enormous quantities of fertilizer that were on the order of more than 10 times recommended amounts. Since it was unclear how these observations could be meaningfully adjusted, we conducted the analysis only for standardized units and also capped N kg/ha at 300.

For each crop, the highest 5 percent of the quantity of fertilizer (nitrogen kg/ha) is also trimmed. Similarly, we trim the highest 1 percent values of other material inputs and labor. Since these inputs are not used on all plots, we do not trim the lowest 1 percent of values (which would be zero quantity – a common occurrence). Two inputs have extremely high quantities reported. The top 5 percentile values of manure (compost) quantity, measured in kg/ha, for millet, sorghum and maize are 17148 (731), 10823 (175) and 32258 (5586). These values lead to average manure and compost application rates being considerably higher than what is considered reasonable. Hence, we trim the 5 percent highest manure and compost quantities applied instead of the highest 1 percent.

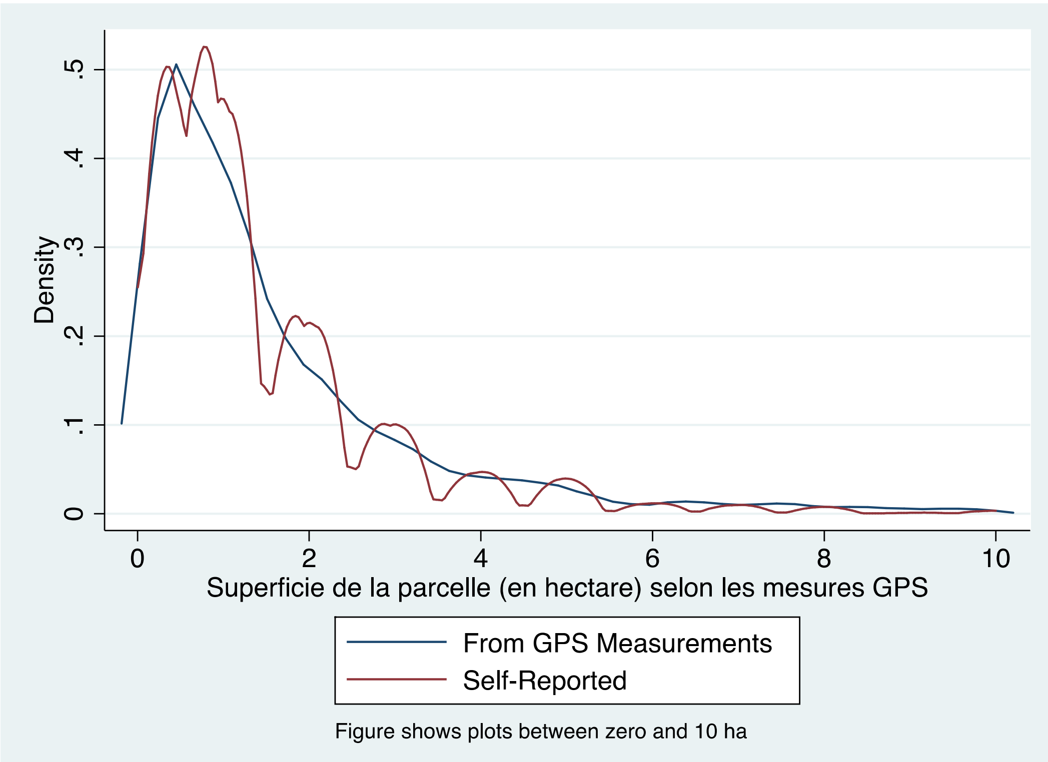
Since crop yield is the dependent variable, we also trim the tails of its distribution. While yields were intended to be measured by objective measurement of yield subplots, they were based on farmer recall of plot production, divided by plot areas. Errors in measurement may have occurred from numerous sources, including difficulty in recalling disaggregated output by plot, and non-standard units (cart, granary, sack, basin, basket) of conversion. About 2% of cereals plots had not been fully harvested at the time of the survey. Crop yields of greater than about 4,000 kg/ha are dropped for millet and sorghum, and 6,000 kg/ha for maize, since these are unrealistic for growing conditions of Mali and likely to be errors in the data. Although average sorghum yields are 4.5 t/ha in the US, an reach 7 t/ha in India, Rattunde et al. (2013) report a maximum of nearly 3 t/ha under farmers' conditions with sorghum hybrids in the Sudan Savanna, a more productive zone. Although farmers can attain up to 4 t/ha of millet in irrigated zones of India, we do not find millet yields reported for Mali that are greater than 1.4 t/ha in the Sahelian zone (Traoré et al. 2017). Regarding maize, the highest estimates we have seen are reported by Coulibaly (8000). Due to these decisions, our estimates may not be very precise for the tails of the yield distribution. However, since we are interested in the effect of fertilizer on the typical farmer, we ensure that extreme values do not drive the results.

More than one crop is grown on many plots. This leads to many issues. One is that the entire area of the plot is not dedicated to the crop, and the fertilizer applied will also be used by the other crop. While the data asks the respondents for the proportion of the plot dedicated to each crop, this is likely to be an inaccurate measure since crops are usually grown next to each other, rather than dividing the plot into separate sections for each crop. Also, the type of intercrop matters – some crops absorb more nitrogen while others do not. Some crops, like legumes, help with nitrogen fixation, which may itself improve the yield of the other crop over sequential seasons. To overcome such problems, only mono-cropped plots are kept in the sample. This leads to 456 (20.0%), 311 (17.6%) and 154 (10.3%) of millet, sorghum and maize plots being dropped from the sample. Inclusion of intercropped plots in the analysis did not improve results.

Another feature of the data is that seed quantities are not reported for about 603 plots, most likely because farmers planting local seed do not measure these exactly. Since this reduces the sample size, the model is estimated with and without the seed variables.

Appendix 2: Additional Figures and Tables

Figure 1: Plot Sizes (Self-Reported and from GPS Measurements)



Appendix Table 2: Dryland cereals yield response to nitrogen nutrient applied, household fixed effects model

Variables	(1)	(2)	(3)	(4)
Nitrogen fertilizer	4.091***	4.289***	4.100***	4.066***
	(0.793)	(0.801)	(0.800)	(0.856)
Millet	-439.1***	-204.1***	-132.1***	-85.36
	(45.66)	(47.57)	(49.66)	(60.09)
Sorghum	-479.3***	-275.5***	-205.3***	-152.5***
	(38.61)	(40.15)	(41.78)	(51.93)
Manure		0.0192***	0.0210***	0.0239***
		(0.00472)	(0.00506)	(0.00607)
Compost		-0.159*	-0.153*	-0.157*
		(0.0891)	(0.0850)	(0.0897)
Other Organic		0.669*	0.589	0.496
		(0.398)	(0.381)	(0.399)
Pesticide		233.0***	282.6***	214.4***
		(45.05)	(43.22)	(65.72)
Fungicide		93.80**	92.68***	106.5***
		(37.19)	(34.10)	(35.68)
Herbicide		80.45***	-11.13	-24.27
		(28.61)	(34.17)	(39.04)
Other Protecting		378.8	685.9	838.1
		(558.1)	(516.9)	(598.2)
Total Labor		2.516***	1.661***	1.583***
		(0.264)	(0.282)	(0.345)
Local Seed			4.854***	5.080***
			(1.177)	(1.430)
Improved Seed			36.63***	45.34***
			(6.220)	(7.795)
Plot Area				-10.08***
				(3.524)
Plot Distance (km)				1.045
				(6.984)
Plaine				81.99
				(96.81)
Plateau				-28.94
				(125.6)
Lowland				169.8
				(145.2)
Soil Sandy				-247.9*
				(147.7)
Soil Clay				-241.9
				(151.4)
Anti-Erosion Structure				153.2
				(153.0)
Constant	1,186***	799.9***	701.1***	839.7***
	(32.80)	(39.14)	(43.52)	(156.7)
Observations	3,327	2,840	2,346	1,834
Number of households	1,374	1,264	1,033	824

Source: Authors, based on LSMS data. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Appendix Table 3: Dryland cereals yield response to nitrogen nutrient applied, instrumental variables-household fixed effects model

Variables	(1)	(2)	(3)	(4)
Nitrogen fertilizer	23.565***	33.371***	38.603***	34.181***
	(5.254)	(9.224)	(9.320)	(9.822)
Millet	-105.839	117.054	339.496**	428.309**
	(97.107)	(129.289)	(153.750)	(197.919)
Sorghum	-	-15.471	148.630	268.860
	(80.085)	(105.556)	(122.590)	(166.956)
Manure		0.013*	0.009	0.013
		(0.007)	(0.009)	(0.010)
Compost		-0.436***	-0.509***	-0.447***
		(0.150)	(0.165)	(0.165)
Other Organic		1.024*	1.243*	1.109
		(0.622)	(0.695)	(0.702)
Pesticide		234.533**	245.439***	94.373
		(64.555)	(70.682)	(109.551)
Fungicide		72.295	71.502	88.921
		(51.835)	(54.208)	(54.375)
Herbicide		-106.563	-165.096**	-126.611*
		(71.729)	(69.203)	(68.767)
Other Protecting		448.849	417.763	364.978
		(829.479)	(878.428)	(995.815)
Total Labor		1.981***	1.848***	1.905***
		(0.416)	(0.486)	(0.576)
Local Seed			1.107	1.248
			(2.114)	(2.484)
Improved Seed			35.782***	39.444***
			(10.083)	(12.286)
Plot Area				-19.208***
				(6.411)
Plot Distance (km)				10.979
				(11.363)
Plaine				-10.457
				(155.981)
Plateau				-118.765
				(200.955)
Lowland				-228.326
				(269.173)
Soil Sandy				-281.665
				(244.712)
Soil Clay				-352.897
				(248.718)
Anti-Erosion Structure				215.939
				(234.328)
Observations	2,453	2,043	1,707	1,307
Number of households	776	671	548	425
Kleibergen Paap F	57.02	21.54	23.62	16.84

Source: Authors, based on LSMS data. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Appendix 3: Entire Plot Representation Soil Sampling Protocol for Smallholder Farms
(Sieglinde Snapp, pers. comm.)

The purpose of this protocol is to obtain a composite (bulk sample) representative of farm plots soil (<0.4 hectares).
Supplies:

- 10 liter pail or bucket (basin also works) CLEAN PAIL BETWEEN FIELDS
- Soil auger OR trowel
- Sample bags to store soil (e.g. strong plastic bags)

Procedure:

1) Familiarize yourself with the plot dimensions
   a. Know where field boundaries are
2) Take sub-samples of soil following a zig-zag path (See below sample diagrams)
3) Collect sub - samples from the ridge **NOT** in the fallow
4) Starting at one corner of the plot go to the 2nd ridge in from the edge, take the first sample
5) Collect 8 sub-samples in each plot, each sample is collected to about 8 in depth and placed in the pail
6) Sub - samples should be taken according to the following: Choose process based on which tool you have for sampling.
   a. Soil auger
      i. Remove all top residues from sampling site (such as leaves and plant materials)
      ii. Insert the auger directly into the soil (20 cm = 8 inches) in a ***vertical (up and down)*** position
      iii. Carefully remove the auger (avoid any spillage of sample). If soil is dry at sampling time, slightly tilt the auger back to avoid it spilling from tube
      iv. Place the sample in the pail and move on to the next
   b. Trowel
      i. Remove residues (such as leaves and plant materials, brush off)
      ii. Insert the trowel ***vertically (up and down)*** into the soil (20 cm = 8 inches)
      iii. Gently push back on the handle and remove the soil (ensuring that you obtain the soil at insertion depth)
      iv. Place the sub - sample in the pail and move on to the next
7) After all 8 of the samples are collected mix up the soil very well and use this soil to fill a bag
   a. Remove any large stones sticks or roots from the sample
   b. Break up any soil clods with your hand
   c. Mix by hand very well for at least a minute until all the soil is homogenized
   d. Collect about one-quarter of the sample to put in a bag (remaining soil should be returned to field)
8) Label the sample bag with the following: Provide an example labeled bag
   a. Date
   b. Sample ID